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INCORPORATING UNCERTAINTY IN THE DESIGN OF STREAM CHANNEL MODIFICATIONS[1]

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ABSTRACT: The designs of stream channel naturalization, rehabilitation, and restoration projects are inherently fraught with uncertainty. Although a systematic approach to design can be described, the likelihood of success or failure of the design is unknown due to uncertainties within the design and implementation process. In this paper, a method for incorporating uncertainty in decision-making during the design phase is presented that uses a decision analysis method known as Failure Modes and Effects Analysis (FMEA). The approach is applied to a channel rehabilitation project in north-central Pennsylvania. FMEA considers risk in terms of the likelihood of a component failure, the consequences of failure, and the level of difficulty required to detect failure. Ratings developed as part of the FMEA can provide justification for decision making in determining design components that require particular attention to prevent failure of the project and the appropriate compensating actions to be taken.
(KEY TERMS: decision making; hydraulics; stream restoration; design; uncertainty, failure; adaptive management.)

INTRODUCTION

Stream restoration, rehabilitation, and stabilization projects are being planned, designed, and constructed at an increasing rate in locations all across the country. Guidelines for designing these projects are often vague and qualitative in their approach. In many cases, the lack of definitive design procedures has resulted in frustration, excessive costs, and poor results.Engineering design is a systematic process that provides a framework for achieving design objectives. The design process includes the following steps: problem definition, solution creation, analysis of solutions, solution evaluation, problem resolution, and solution implementation.

For stream restoration, this type of systematic approach results in the following set of steps:

1. Define the problem by assessing channel stability and habitat conditions, setting clear and specific objectives for the project, and assessing risks and constraints.

2. Create solutions by determining design alternatives to achieve objectives.

3. Investigate solutions by collecting and analyzing the required data to determine the design loads and parameters.

4. Evaluate the solution by determining possible upstream and downstream impacts for each design and by eliminating alternatives based on risk, constraints, and impacts.

5. Finalize the design based on the best alternative according to the solution evaluation.

6. Implement the solution and develop a monitoring plan.

Although the design process is conceptually straightforward, there are many factors in stream modification designs that complicate this process. Some of these factors include: (1) objectives are often vague and, thus, it is difficult to develop specific solution alternatives that would achieve the objective; (2) interference in the design caused by road crossings

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is quite common, especially in urban and suburban areas; (3) other urban constraints, such as lack of lateral easement and existing infrastructure (e.g., water lines, sewer lines, and culverts), do not permit the design of a naturalized stable channel; (4) each restoration site is unique and the underlying causes of the observed disturbance are often complex and difficult to unravel so that a single set of design guidelines is unable to globally address issues at a given site; (5) river restoration projects are, or should be, highly interdisciplinary, often resulting in communication problems between the disciplines; (6) geomorphic and ecologic responses and time frames for responses to a given design are complex and difficult to predict; and (7) existing problems are often due to multiple causes.

The lack of definitive design guidelines and the complexity of the geomorphic and ecologic system result in a relatively high degree of uncertainty in modifying a stream. Adaptive management was developed as a method to make informed decisions regarding river restoration that embrace uncertainty (Holling, 1978; Walters, 1986). Adaptive management is based on formal experimentation (as opposed to trial-and-error), attention to scientific uncertainties in processes and responses, and experimental design and hypothesis testing to reduce uncertainties (NRC, 1999). In addition, adaptive management uses information gained through careful monitoring of the restoration site to guide future decisions. Thus, a central component of designing and adaptively managing a stream restoration project is acknowledgment of the uncertainty, and thereby risk, in our understanding of the complex system. In this paper the sources of uncertainty and the impact on stream restoration design are described. Methods for incorporating uncertainty are also presented.

SOURCES OF UNCERTAINTY

Adaptive management evolved from the notion that stream restoration is often replete with uncertainty in all phases of the restoration project, including design, implementation, and monitoring. Adaptive management embraces these uncertainties for making decisions during all three phases (Walters, 1986; McLain and Lee, 1996; Thom, 1997; Kershner, 1997). Uncertainty primarily results from our lack of knowledge; it is generally reduced as our knowledge and understanding of complex river processes and responses increase. Uncertainty leads to a risk of failure and so it is critical that it is acknowledged in stream restoration activities.

There are several broad categories of uncertainty that are common to any design process. These include:

- **Model Uncertainty**. This results from attempting to describe a complex physical process or phenomenon through the use of a simplified mathematical expression. Examples of models used in stream restoration designs include regional regression equations, sediment transport equations, and ecological response models.

- **Parameter Uncertainty.** This type of uncertainty results from difficulties in estimating model parameters. For example, Manning's roughness coefficient and dominant discharge are two common stream design parameters that cannot be measured directly; therefore, they must be estimated or assumed. The result is parameter uncertainty.

- **Randomness.** Natural (or inherent) randomness is a source of uncertainty that includes random fluctuation in parameters, such as flow discharges and velocities.

- **Human Error.** There is always potential for human error in design and in the actual implementation of a design. This type of uncertainty includes calculation and construction errors.

In a stream restoration design, there are many individual factors which contribute to each of these categories of uncertainty, thereby decreasing the reliability of the design (Johnson, 1996; Johnson and Rinaldi, 1998). Specific sources of uncertainty are described below.

Ecosystem and Physical System Modeling

Models are used in the stream restoration process for two primary purposes: design and response predictions. Equations and models are used in the design process to quantify any number of parameters, including cross sectional geometry, planform geometry, sediment transport, shear stresses within the channel and on the floodplain, and velocities and flow depths for a range of flow conditions. Response models are used to calculate the physical or ecological response to changes in the physical system, such as the stability of a channel, the long-term sediment transport conditions, and local scour and fill patterns. Regardless of the purpose, all of these models are mathematical representations, and typically simplifications, of complex physical processes and phenomena. Most of the models are either semi-empirical or completely empirical and, as such, are based on data from specific regions, watersheds, or reaches. Thus, while the models may work well for certain situations or settings, they may work poorly for others. In addition, a full understanding of these complex phenomena has not been achieved. The result is that there are no models that can accurately predict all of the responses to change in the physical system for all settings and conditions. Therefore, varying degrees of uncertainty are associated with the use of these models. Generally speaking, model uncertainty is often the primary source of uncertainty.

Restoration Objectives

Setting objectives for any design is required so that the purpose of the design can be mėt. In stream restoration projects, the objectives are often vague because of the difficulty in setting specific, measurable objectives. Thus, vague objectives, such as improvement of the aquatic or riparian habitat, physical stability of the stream, or aesthetic qualities of the stream corridor, are often stated as the project objectives. To set more specific objectives than these, the definition of improvement or stability in the physical system and ecosystem must be clearly articulated. For example, a stated objective might be to improve the aquatic habitat. This vague objective does not indicate a measurable goal, such as a specific desired reduction in water temperature, an increase in flow diversity, or an increase in the diversity or number of species. Another common objective is to create a stable channel. In this case, acceptable levels of bank and bed erosion and lateral migration should be clearly stated in terms of a magnitude per year or other quantity, particularly where urban and suburban development is limiting the river's lateral movement. Without specific objectives, the design success in achieving the objectives will be unknown. Clearly defined objectives are also required for meaningful monitoring following the construction of the project site so that monitoring data can be used to assess the success or failure of the project.

Vague Definitions

Tied to the ability to set clear, specific objectives is the problem of defining various terms that describe the ecologic or physical condition of a stream. For example, vague definitions can be given for channel stability, ecologic diversity, and project failure. However, providing specific, measurable definitions such that the response and outcome of the project can be measured and a degree of success can be associated with the level of achievement of these terms is far more difficult. Thus, uncertainty exists because there is an inability to accurately define important terms that are used to assess the state of the stream corridor.

Vague Design Procedures and Guidelines

Rosgen and Fittante (1986) propose that failures of instream habitat improvement projects are due in part to the lack of field experience and documented procedural guidelines for using these methods. Although stream restoration guidelines have been established by several government agencies, they are often rather vague and rarely differentiate between varying physiographic and geologic conditions. Most manuals describe the design process qualitatively or quantitatively or both. However, the causes of the problems in a given stream corridor are numerous and complex and the remedy will vary by geologic and physiographic regions as well as the level of urbanization. Given the uniqueness of each restoration site and the inability to quantify the response of the system to changes, it remains that a well designed restoration project requires field experience as well as design procedures. Thus, there is considerable uncertainty due to an inability to incorporate experiential understanding of complex river systems into the design guidelines.

Parameter Estimation

Parameter uncertainty results from an inability to accurately assess parameters and coefficients required in models. There are a variety of parameters associated with river restoration that are difficult to estimate with certainty. A few examples include the bankfull elevation and width, asymmetric and irregular meander dimensions, and the roughness coefficient or friction factor. Approximate or average values are commonly used for these parameters which may lead to a somewhat inappropriate and uncertain design.

Monitoring

Monitoring is an essential component of any stream restoration project and adaptive management schemes. Data acquired during monitoring are used to determine the degree of success of the restoration project and to provide input into additional remedies. However, there is considerable uncertainty in the monitoring process. It is unclear how many data, what types of data, and what locations should be monitored following construction of the restoration project. When data are collected, they are analyzed to assess the health and success or failure of the project. Because the objectives are frequently vague, it is difficult to interpret the results of the data analyses in terms of success or failure or the need for further modifications. It is also not readily apparent when and for what hydrologic events monitoring should take place. Should a stream be monitored during a rising/falling hydrograph or after the hydrologic event when the flood waters have receded? Many county and state jurisdictions have policies that require three to five years of post-construction monitoring. The selection of the monitoring duration is somewhat arbitrary, but tends to be the length of time over which streams make their primary adjustments to their new planform, cross-sectional geometry, and in-stream measures. However, there is much disagreement as to the appropriate length of time for monitoring activities. Thus, uncertainty in monitoring protocol yields uncertainty in assessing whether the objectives have been met and in the implementation of further remedies.

Scale

There are several issues related to scale in stream restoration. First, many stream restoration techniques discussed in the literature and in design guidelines are developed for small to moderate streams. The ability to transfer those design practices from one scale to another has not been well established. Therefore, the likelihood of the implementation of these techniques on larger rivers is unknown and fraught with uncertainty.

A second source of uncertainty is related to the scale over which the restoration is performed. Often, restoration efforts cannot be performed over the entire length of the river due to various constraints and limitations. Thus, decisions must be made regarding the locations and extent of restoration sites. The reach lengths and proximity of the disjointed reaches to each other, in part, dictate whether or not the restoration will succeed in creating a self-sustaining, resilient stream channel. However, the optimum reach lengths and spacings are unknown and, thus, contribute to the overall uncertainty.

Climate Change

It is well established that climatic changes are occurring in large areas around the world due to both natural and human-induced activities. The effects of climatic changes can include increases or decreases in air temperature and changes in hydrologic regimes. The effect of such climatic changes on the ability of a stream restoration project to continue to be self-sustaining over a long period of time is unknown. In addition, the direction and magnitude of the change is unknown and is a subject of great debate.

Land Use Changes

Changes in land use within a given watershed often result in a change in the boundary conditions, i.e., the flow and sediment discharges delivered to a river reach. For example, a change from agricultural to urban or suburban may result in an increase in flow discharge and a decrease in sediment discharge. If these changes take place during the restoration design and implementation, the result may be failure or partial failure of the project. In addition, changes in the boundary conditions in the years following a restoration implementation can also result in the eventual failure of the project. It is difficult to include the expected boundary condition changes in the restoration design since the restoration must be primarily designed for current conditions so that it does not experience instability. Thus, uncertainty in future land use changes and uncertainty in the method for incorporating expected land use changes results in uncertainty in the overall design.

Construction and Implementation Practices

There are a number of sources of uncertainty involved in the implementation of a restoration project. An experienced construction crew can markedly improve the likelihood of success of a project. Many problems are encountered in the field that may be overlooked in the design phase which will then require experienced personnel to solve on site. In addition, inadequate supervision of the construction project by the design team can lead to inappropriate decision making on site. Human error in measurement, placement of measures, or excavation can also lead to partial or complete failure of the project. It is always difficult to account for human error in a project design; however, this type of uncertainty can be reduced by assuring that the field crew is experienced and that there is constant communication between the crew and the designer.

INCORPORATING UNCERTAINTY INTO DESIGN

It is not a trivial matter to quantify uncertainty. Methods, such as first-order analyses and Monte Carlo simulation, are frequently used to compute uncertainty. For these methods, a mathematical model, coefficients of variation, probability distributions, and joint probability distributions are required. Many of the sources of uncertainty described above are not readily quantifiable and cannot be directly incorporated into a model predicting system response. In addition, models are not available for many aspects of stream restoration, such as the quantification of channel response to a disturbance. Qualitative models may exist, but it is difficult to associate a quantitative value to these models.

An alternative to the direct calculation of uncertainty is to include it in the decision-making process. Incorporating uncertainty into decisions regarding stream restoration design, implementation, and monitoring is a key component of adaptive management. Embracing uncertainty allows the restoration practitioner to incorporate or at least consider multiple causes of existing problems or to consider multiple hypotheses. It may also help to reduce the costs of restoration projects in that the projects will be less likely to have to be redesigned or reconstructed if multiple hypotheses are considered initially.

There are a number of methods available for qualitatively, semi-quantitatively, or quantitatively assessing the causes and effects of a wide variety of factors in uncertain, complex systems and for making decisions in light of uncertainty. These methods, including fault tree analysis, decision trees, and failure modes and effects analysis (FMEA), are based on analyses of failures. A potential failure can be affiliated with a failure cause, a failure mode, and a failure effect, although these are sometimes very unclear and difficult to define in real-life situations (Rao, 1993). A failure mode is the manner in which a system or system component may fail to meet design intent (Bluvband and Zilberberg, 1998). For a failure mode analysis of any type, it is of paramount importance to first define what constitutes a system failure (Krasich, 2000).

In the context of river and stream modification design, failure modes may bring about functional or structural failures, thereby jeopardizing project goals and objectives. A structural failure is identified as a collapse of the physical system or components of the system sufficient to prevent fulfillment of the design objectives. A functional failure implies that the project objectives cannot be realized due to the ineffectiveness of the design, although the structure or form may be intact and in place. Since the fulfillment of structural objectives is a prerequisite to other restoration and stabilization targets, the occurrence of structural failures will be the focus of this paper.

Fault Tree Analysis

Many failure phenomena can be systematized as a chain or hierarchy of events, thereby linking causes of some events to the effects of others (Rao, 1993). Ultimately, a detailed hierarchy of contributing events to the top-level system failure event can be established. A fault tree is a diagrammatic representation of these relationships among component-level failures and system-level undesired events. Fault tree analysis is a structured procedure used to graphically define the hierarchical relationships among a system failure and component failure modes. A fault tree can assist in the identification of paths to failure and can be used to single out critical events. Fault trees also can be used to assess the probability of failure for the system (or top event), to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of the top event, and to determine the sensitivity of the probability of failure of the top event to various contributions of basic events. Fault tree analysis has been implemented to model a variety of engineering applications including the causes of construction falls (Hadipriono, 1992), bridge failures resulting from scour and stream instability (Johnson, 1999), failure of urban infrastructure following stream restoration (Hess and Johnson, 2001) and the failure of coastal flood protection measures (Vrijling, 1993).

Fault tree analyses can be either qualitative or quantitative, depending on the desired output. Qualitative analyses provide information about the importance of the basic events. Cut sets are commonly used for this type of analysis. A cut set is a combination of terminal events that is sufficient to cause an occurrence of the top event (Sundararajan, 1991; Ayyub and McCuen, 1997). In other words, if all terminal events in a cut set occur, then the top event will occur. A minimal cut set is defined as the smallest subset that is sufficient and necessary to cause the occurrence of the top event. In a quantitative fault tree analysis, the top event is related to subevents and basic faults through gates representing mathematical operations for combining the probabilities of those events. The calculation of the probability of occurrence of the top event is is a function of the probabilities of the basic events and the type of gate. If all events in a fault tree are independent, then the calculations are straightforward. However, if some of the events are dependent, then information regarding the conditional probabilities is required.

There are several drawbacks to the use of fault tree analysis for complex systems, such as a river system. First, a quantitative analysis requires probabilities of occurrences for all events contributing to failure as well as conditional probabilities for dependent variables. These are rarely known in river systems. Second, for very complex systems that require large fault trees, it is possible to overlook or miss failure modes (Sundararajan, 1991). In this case, the probability of occurrence of the top event or other events could be nonconservative. Third, there are only two possibilities of the occurrence of any event; the event either occurs or it does not. Fuzzy or changing failure modes cannot be readily accounted for.

Decision Trees

Decision trees, commonly used in engineering and management applications to evaluate and reduce risk, are ideally suited to choosing an optimal alternative or option for a system design or problem. Used in this context, alternatives refer to choices or decisions and should not be confused with physical system components such as bank stabilization alternatives. To achieve this goal, decision trees can be used to effectively evaluate the consequences of a sequence of decisions (i.e., list of feasible alternatives or options) by calculating corresponding probability assignments and resulting utility values to be used for the purpose of comparison (Ang and Tang, 1984). Ultimately, the decision as to which alternative is superior depends on the relative utility values calculated for all potential outcomes.

One of the drawbacks of decision tree analysis is that probabilities are required for each alternative and outcome. As with fault tree analysis, these probabilities are rarely known. In addition, the calculation of a utility value requires the costs associated with each alternative and outcome.

Failure Modes and Effects Analysis (FMEA)

FMEA is a qualitative procedure to systematically identify potential component failure modes and assess the effects of associated failures on the operational status of the system (Dushnisky and Vick, 1996). FMEA is performed prior to design implementation so that the risk of component or system failure can be assessed and changes to the design implemented at low relative cost. The following are required to execute a FMEA (McCollin, 1999):

- a hierarchical structure for the system illustrating all system components,
- failure modes of all components of the system, and
- an objective criterion for implementing corrective action (the most commonly used is the risk priority number).

Due to the hierarchical nature of composite systems, failure modes exist at differing levels of detail or scale; therefore, analysis of the system starts with failure at the lowest level of scope and describes how the next higher level is affected.

In the past, FMEA has been used to advance the understanding of complex electrical and mechanical systems including numerous applications in nuclear safety (e.g., McCormick, 1981; American Nuclear Society, 1983; Fullwood and Hall, 1988; Henley and Kumamoto, 1992; Shimizu *et al.,* 1993) and to evaluate and rank potential problems in manufacturing processes. Formulation of the FMEA begins with identification of the system and all of its components (Dushnisky and Vick, 1996). Next, the range of possible failure modes is defined as mutually exclusive, collectively exhaustive events. Basic sources of failure modes typically include documented case studies, laboratory experimentation, field experience, and expert opinion. Once the failure modes are identified for each component of the system, their effects on the system and other system components, consequences, likelihoods of occurrence, methods of detection, and compensating provisions (i.e., possible corrective actions) are listed. The system designer arbitrarily chooses numeric ratings (e.g., 1 through 10) for these criteria, with the largest values associated with the most severe consequence level and the highest likelihood of occurrence. By using ratings for consequences and occurrences, in addition to a rating for detectability (likelihood that the failure mode will be observed), failure modes can be prioritized to focus a greater level of effort on higher priority failures.

The most common method of establishing prioritization among failure modes is through the implementation of risk priority numbers. A risk priority number (RPN) is a characteristic quantitative result from a FMEA used to suggest the appropriate nature and extent of corrective actions for failures at all levels of system scope. The RPN is the product of the occurrence, consequence, and detectability ratings of a given failure mode, although other factors may be included in an advanced FMEA, such as associated cost and required resources to implement corrective actions (Bluvband and Zilberberg, 1998). Even though the ratings are somewhat arbitrary labels rather than numbers representing explicit numeric quantities, the relative values can be compared and used to prioritize failures. Failure modes having a high relative RPN (i.e., a high risk) are assumed to have a larger impact on system failure than those with a lower RPN.

Use of the risk priority number can be highly subjective if the criteria for determining its value and its implication toward corrective adjustments are not adequately defined prior to conducting the FMEA. Numerical values for consequence level, occurrence frequency, and detectability need to be established as a preliminary step to any analysis. Associating degrees of corrective action with ranges of RPNs prior to analysis requires establishing numeric values for thresholds and cutoff points to define these ranges.

EXAMPLE OF INCORPORATING UNCERTAINTY INTO CHANNEL MODIFICATION DESIGN

The Bentley Creek watershed is located in the north central portion of the Susquehanna River basin, comprising the northwestern section of Bradford County, Pennsylvania, and the southeastern section of Chemung County, New York. Three key problems were identified at the Bentley Creek site dating back to the occurrence of Hurricane Agnes in 1972: (1) streambank erosion, resulting in large property losses and endangerment of homes and businesses located near the stream channel; (2) increased sedimentation resulting in aquatic habitat destruction and blockage of bridge openings; and (3) heightened flood stages from partial reduction in channel capacity (U.S. Department of Agriculture, 1997).

A 1997 survey of the extent of Bentley Creek by the Natural Resources Conservation Service (U.S. Department of Agriculture, 1997) identified 78 percent (33,465 feet) of the main stem of Bentley Creek as having unstable banks. Some practices aggravating the situation included inappropriate and inadequate channel modification and stabilization efforts, insufficient bridge openings, lack of adequate riparian vegetation (resulting from Hurricane Agnes and subsequent efforts to clear debris from the channel with heavy machinery), debris blockages, and development in the stream's riparian zone.

In November 1998, a decision was made to modify Bentley Creek in an effort to:

- reduce or eliminate flood damages to Wellsburg, New York, and Ridgebury Township, Pennsylvania;
- arrest the deposition of sediment blocking stream channels and bridge openings; and
- significantly reduce streambank erosion to protect life and property.

One mile of the main stem of Bentley Creek was to be reconfigured with the addition of three meander bends and a modified cross sectional geometry to help decrease flow velocity and constructed with an enlarged floodplain to decrease flood flow energy. Instream measures were to include single-wing vanes, cross vanes, and root wads to fulfill local stability objectives including flow redirection and grade control.

FMEA is used here to illustrate a relatively simple technique to incorporate uncertainty into the design process for the Bentley Creek project. The basic setup for the FMEA is given in Table 1. Column 1 provides the components of the project, which include local measures (vanes, cross vanes, and root wads) as well as modifications to the channel itself (change in the cross sectional geometry, localized channel relocation, and meander construction). The local measures are used for bank stabilization and to direct the flow away from road embankments. The cross section was to be changed to contain the estimated dominant flow. Downstream of one of the bridges, the channel was to be moved so that the angle at which it met a tributary was reduced. Meanders were to be constructed to approximate the sinuosity that existed prior to channel straightening. In Column 2, the failure modes for each component are given based on experience, prior failures at other sites, and knowledge of channel adjustments. Columns 3 and 4 describe the anticipated local and system-wide effects, respectively, of the stated failure mode associated with a specific component. Column 5 describes methods for detecting failure based on field experience and documented case studies. Column 6 gives compensating provisions, or possible corrective actions, should failure occur. Columns 1 through 6 must be established prior to calculating RPNs and prior to taking action to reduce uncertainty.

The calculation of RPNs requires that consequence, occurrence, and detectability ratings are first established. Tables 2 through 4 were developed to provide these ratings for this example. As stated previously, the rating scales given in these tables are chosen arbitrarily. In this case, the various factors are given ratings of 1 through 10. The failure or partial failure of a stream restoration project has impacts both economically and environmentally, particularly in terms of available habitat. In addition, public scrutiny of the project can have an enormous impact on future projects. Thus, Table 2 reflects these three outcomes categorized into four levels of consequences. Table 3 is primarily based on prior experience using these types of designs as well as characteristics of Bentley Creek

TABLE 1. FMEA Example for Design of Bentley Creek Project.

Components (1)	Failure Mode (2)	Effects on Other Components (3)	Effects on Whole System (4)	Detection Methods (5)	Compensating Provisions (6)
Vanes and Cross Vanes	Burial by incoming sediment	None or minimal	Minimal	• Measure has a lower profile	• Re-orient or reposition measure
	Rapid lateral migration away from vane from vane	None or minimal	May cause property or infrastructure damage	• Bank retreat at bank pins • Proximity to structures and/or survey marker	• Armor opposite bank • Construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around measures	Minimal, some sediment input	• Bank retreat at pins • Raw banks • Undercutting of bank	• Re-orient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	• Scoured pool position incorrect • Scour around bankside of vane	• Re-orient or reposition measure
Rootwads	Excessive scouring	Additional erosion at d/s measures	Rapid bank erosion following failure; sediment input	• Scalloped banks between wads • Root wad popped out	• Add additional rootwads • Use alternative measures
Cross Sectional Geometry Change	Rapid widening	Failure of adjacent measures	Sediment input; local to regional property or structural loss	• Rapid bank retreat at bank pins • Increased channel width • Geotechnical failure planes	• Alter bank side slopes • Add vanes and/or cross vanes • Armor banks • Adjust channel
	Excessive deposition (too wide)	Burial of other measures	Increased flooding	• Measures have lowered profile • Bed elevation increase • Decrease in longitudinal slope	• Decrease channel width • Install vanes and/or cross vanes
	Bed Degradation (too narrow)	Undermining of measures	Eventual bank collapse, loss of overbank habitat	• Bed elevation decrease • Undermining of measures • Headcuts	• Widen channel • Install weirs or check dams • Install deflectors to encourage bank widening
Channel Relocation Downstream of Bridge	Channel migration	Burial of other measures; undermining of other measures	Loss of property	• Bank retreat at bank pins • proximity to structures and/or survey marker	• Install vanes on migrating side • Armor banks
	Excessive deposition d/s of bridge	Minimal	Loss of conveyance at bridge, increased flooding	• Bar formation • narrowing of channel	• Install vanes and/or cross vanes; narrow and/or straighten channel

TABLE 1. FMEA Example for Design of Bentley Creek Project (continued).

Components (1)	Failure Mode (2)	Effects on Other Components (3)	Effects on Whole System (4)	Detection Methods (5)	Compensating Provisions (6)
Meander Construction	Rapid lateral or downstream meander migration	Burial of other measures; undermining of other measures	Loss of property; failure to convey Q and Q_S*	• Bank retreat at bank pins • Proximity to structures and/or survey marker	• Install vanes on migrating side • Armor banks
	Excessive deposition	Burial of other measures	Increased flooding	• Measures have lowered profile • Bed elevation increase • Decrease in longitudinal slope	• Install vanes and/or cross vanes • Narrow and/or decrease sinuosity

*Q_S is the sediment discharge (load entering restoration reach). Qs can be decreased at either the watershed or reach level, depending on the source of the material. At the watershed level, steps must be taken to decrease sediment input into the stream. At reach level, steps must be taken upstream of the project reach to reduce bank widening and/or bed degradation.

TABLE 2. Consequence of Categories.

Consequence Category	Loss of Life	Outcomes of Failure: Economic Impact	Aquatic Habitat Impact	Public Scrutiny	Rating
I (Low)	None	• Minimal replacement cost relative to project budget • Susceptibility to failure of other measures is not increased • No or minor impacts to public and/or private property	No or minor short-term negative impacts in localized areas	Low	1
II (Marginal)	None	• Moderate replacement cost relative to project budget • Replacement of supporting or integrated enhancement measures required • slight to moderate public and/or private property damage (e.g., minor roadway embankments compromised)	Moderate short-term negative impacts in localized areas	Moderate	4
III (High)	None	• Moderate to high replacement cost relative to project budget • Replacement of a significant portion of the project • Failure of minor infrastructure, moderate to high public or private property damage	Not used to identify high impact levels	High	7
IV (Critical)	Possible	• High replacement cost relative to project budget • Replacement of a significant portion of the project • Failure of hydraulic or engineering infrastructure; loss of service provided by infrastructure and/or public utilities; high public or private property damage	Not used to identify critical impact levels	High	10

prior to project implementation. The categories and ratings in Table 4 were based on the level of difficulty to detect channel adjustments, ranging from visual observations to installation of equipment, such as scour chains or pressure transducers.

For each component and failure mode, ratings were assigned for consequence, occurrence, and detectability. These are given in Table 5. The RPNs were calculated as the product of the three ratings. As shown in Table 5, rapid channel widening and

TABLE 3. Occurrence Likelihood.

Occurrence Likelihood	Rating
Impossible or has never occurred previously	2
Remotely possible; similar events may have occurred previously	4
Possible; has previously occurred rarely	6
Probable; has previously occurred occasionally	8
Reasonably probable; has previously occurred frequently	10

TABLE 4. Detection Rating.

Detection Methods	Rating
Simple visual from field inspection	1
Simple analysis from photo record, bank pins	4
Cross sectional or longitudinal surveys; pebble counts; sediment sampling	7
Scour chains, pressure transducers, on other in-situ installations required	10

TABLE 5. Risk Priority Numbers for Bentley Creek Restoration Project.

Component	Failure Mode	Consequence Rating	Occurrence Rating	Detection Rating	Risk Priority Number
Vanes and Cross Vanes	Burial by incoming sediment	1	6	1	6
	Rapid lateral migration away from vane	1	4	4	16
	Erosion of opposite bank	4	6	1	24
	Ineffective angles	1	4	1	4
Rootwads	Excessive scouring	4	8	1	32
Cross Sectional Geometry Change	Rapid widening	4	8	4	128
	Deposition	4	8	4	128
	Degradation	4	4	7	112
Channel Relocation	Channel migration	4	4	4	64
	Excessive deposition d/s of bridge	7	4	1	28
Meander Construction	Rapid meander migration	7	4	4	112
	Excessive deposition	4	10	1	40

sediment deposition due to the change in cross sectional geometry received the highest RPNs. As the channel widens (due to bank failure), significant amounts of sediment can be added to the flow, similar to the problem in this stream prior to restoration. The sediment is then deposited downstream, typically at an over-widened cross section, a meander or bridge, and causes an increase in flooding as well as loss of property as channel widening removes bank material from private property. Thus, the greatest emphasis should be placed on developing a cross sectional geometry that can efficiently convey the sediment and water load, yet not produce shear stresses that will cause bank erosion. Local measures, such as vanes, can be used to assist in this effort. Based on the low RPNs for these in-stream structures, provided that the cross sectional geometry is appropriate, failure of a vane will not produce a high level of risk for the project. Degradation due to the change in cross sectional geometry and rapid meander migration due to meander construction also received relatively high RPNs. Thus, particular attention should be paid to the ability of the channel to convey its load and to proper armoring of bends, particularly at bridges and other sensitive locations.

CONCLUSIONS

Uncertainty is an important aspect of stream restoration and other channel modifications. Adaptive management has been used in a variety of ways in an attempt to address and incorporate uncertainty in design, implementation, and monitoring. To assist in this effort, it is desirable to have a simplified technique for incorporating uncertainty into the decision making process during the design and post-construction monitoring of a restoration or other modification project. Failure modes and effects analysis (FMEA) was used here to demonstrate a relatively simple technique for assigning relative ratings to all components at the design phase. The ratings can then be used to determine components of the design that require particular attention to prevent failure of the project. This information yields the appropriate compensating actions to be taken and provides justification for decision making. FMEA is an appealing method because it considers risk in terms of the consequences of failure, the likelihood of a component failure, and the level of difficulty required to detect failure.

The method demonstrated here for incorporating uncertainty is a decision tool based on a given design. It does not address whether a project will be successful in meeting the project objectives. For example, the objective of the Bentley Creek project was to alleviate downstream aggradation and and reduce property loss due to bank erosion. The use of FMEA could not evaluate whether these objectives would be met.

The Bentley Creek example provided a demonstration of incorporating uncertainty into the design phase of the project. With a "design-not-to-fail" philosophy, FMEA is implemented to determine failure modes and remove their causes before the design is implemented (McCollin, 1999). Thus, the preventative action in the FMEA implies modification of the system design for risk reduction before the design is in place. A slight modification of this technique referred to as Failure Modes, Effects, and Criticality Analysis (FMECA), can also be used in a similar way for monitoring in the post-construction phase. As with FMEA, FMECA is used to evaluate the importance of failure effects on a system's performance (Shimizu *et al.*, 1993). The main point of note is the FMECA provides a basis for carrying out appropriate corrective action once failure has occurred while there is time for these actions to have significant impact on a proper system performance (McCollin, 1999). Apart from a few subtle points of difference in terminology, FMECA is applied in the same manner as FMEA.

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